Public Infrastructure Service Flexibility for Response and Recovery in the Attacks at the World Trade Center, September 11, 2001

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Introduction

After the terrorist attacks on the World Trade Center in New York City on September 11, 2001, the ability to rapidly restore transportation, power, water, and environmental services to users was absolutely critical, especially to those involved in the immediate search, rescue, and recovery operations. What better way could infrastructure serve its users—both emergency workers and the general public—than to be able to respond quickly in a crisis? The ability to provide these services required a degree of flexibility, often unanticipated and unplanned, that only became apparent as the response efforts unfolded.

The capability of basic infrastructure service providers to respond to public needs for transportation, energy, communication, water, sanitation, and solid waste removal after the September 11th attacks was to a great extent influenced by the flexibility of the initial infrastructure design and management functions to respond to normal system disruptions and to extreme, but not necessarily terrorist-related, events.

The Concept of Flexibility: Definitions and Significance

The ability of physical systems and human services to respond rapidly to user needs is a broad measure of flexibility, and is the focus of this paper. The concept of flexibility as used in this research encompasses both the flexibility of physical configurations and the flexibility of social institutions to bring about changes that enable a system to return to its existing state or to an improved one.

What makes flexibility difficult to define precisely is that it can depend on specific objectives as well as the broad social and environmental contexts in which those objectives play out. Attributes of flexibility as applied to infrastructure services may differ, for example, when the objective is to resist failure or survive shock as opposed to when the objective is for system improvement, such as expansion, in a non-crisis environment.

Flexibility is often related to or associated with other traditional or technical concepts such as resiliency, robustness, redundancy, diversity, adaptability, and interoperability. These are described extensively in the scientific and engineering literature (for a brief summary and references see Zimmerman, 2001). Redundancy is a concept that is often considered synonymous with flexibility, although it is but one component of it. Redundancy has been defined in the context of the physical aspects of communications infrastructure as "having extra capacity available, generally from more than one source" (U.S. General Accounting Office, 2003, p. 92). Diversity, another related term, "involves establishing different physical routes . . . and using different equipment along those routes . . ." (U.S. General Accounting Office, 2003, p. 92).

Flexibility, as used in this paper, is broader than (and encompasses) these other concepts, giving greater emphasis to the socioeconomic, political, organizational, and environmental contexts of infrastructure systems and its explicit interdisciplinary character. In its most general construction, flexible infrastructure supports behavior that does not compromise the goals of the users of the service and includes the ability to change or adapt. An operational definition of the concept of flexibility is provided below in terms of criteria.

Research Objective

The research objective underscores the importance of building in flexibility early in infrastructure decisions. The research hypothesis is:

> If the initial design and operation of an infrastructure service is flexible in dealing with user needs, it will be flexible in reducing the adverse consequences of a crisis.

Methods and Procedures

Zimmerman (2003b) evaluates many specific measures for infrastructure characteristics and behavior with respect to user needs before, during, and after the September 11th disaster at the World Trade Center. These measures are used to test the hypothesis that flexibility supports the performance of infrastructure in crises if it is incorporated as a basic or fundamental characteristic of infrastructure services. Infrastructure as used in this research encompasses transportation, energy, communication, water supply, wastewater treatment, and solid waste management services.

Criteria to Characterize Flexibility

In order to operationalize the concept of flexibility for infrastructure services, several guiding principles or criteria are used to identify and characterize flexibility as it applies to infrastructure services. These criteria provide one basis for designing measures to evaluate how the infrastructure performed on and after September 11th. The criteria below apply primarily to systems facing crisis conditions.

The first criterion is the existence of **alternative routes** to build new capacity or redistribute existing capacity between the sources of production and the intended users (including emergency workers) whose services have been curtailed or otherwise diminished as a consequence of an extreme event. A corollary to this is the existence of **alternative production facilities and locations** as well that permit production to be rerouted or otherwise substituted in an extreme event.

The second criterion is managerial and organizational capability and capacity to **quickly identify, acquire, and manage resources** needed for the safety and security of the population, including knowledge of how those systems operate and the power to control them in a crisis. It includes materials, labor, and supplies for construction as well as to support workers, residents, and business operations. In the management literature these resources are often referred to as “slack resources” (Pfeffer and Salancik, 1978, p. 275), that is, extra resources that can be mobilized when needed. This ability is usually considered an important characteristic of disaster management.

Third is the ability to **transfer information** to users about the state of the system and the alternatives available to them in a way that is simple to use, easy to understand, and can be rapidly disseminated in order to reduce the consequences of a crisis that are specifically related to infrastructure.

Approach

The approach consisted of the following steps to explore the validity of the hypothesis:

- Numerous activities or conditions were identified that involved the use of infrastructure immediately following the attacks and thereafter. The overall research project is incorporating events well beyond this period, however, in order to ascertain the longer-term responses of the infrastructure and to evaluate characteristics other than flexibility.

- Measures were identified or developed for characteristics and behavior of the infrastructure services in conducting those activities, such as the extent to which people used the infrastructure, how long it took to obtain the service, the adequacy of service capacity, and the overall availability of facilities and services.

- The criteria above were then used to characterize the flexibility of the infrastructure services before September 11th and to ascertain the role flexibility played in the provision of infrastructure services during and after the September 11th disaster.

Many information sources were used to identify and analyze events that relied heavily upon infrastructure and how infrastructure was used. These sources included documents and reports, and presentations by public and private owners, operators, and regulators of infrastructure at meetings, conferences, and workshops. The extensive media coverage during and after the September 11th disaster also was a critical resource. The data used span many months following September 11th.

Assumptions

An underlying, operational assumption of the research is that flexibility is a key attribute of and benefit to crisis response capability. It is clear, however, that flexibility does not always lead to desirable outcomes. That is, under some conditions, the same attributes that promote flexibility may also be detrimental. For example, co-location of different systems on the one hand promotes rapid transfers among systems (e.g., shifts from one water line to another) and economies in construction and maintenance, but can also lead to catastrophic failure across all of these systems if they are affected at the same time. The findings of the research are discussed in terms of both the positive and negative aspects of flexibility.

Selected Findings

Numerous success stories during the period immediately following September 11th portray the positive role of flexible infrastructure systems, in particular, in light of flexibility that predated September 11th. Instances are also noted in which systems that were inflexible before September 11th are likely to have contributed to a more adverse impact at the time of the attacks than might have otherwise occurred. Although each infrastructure system is evaluated separately in this section, numerous interrelationships existed among them and the role of these interdependencies in enhancing or inhibiting flexibility on a systemwide scale is a part of the analysis, presented below in the section on Understanding Infrastructure Interdependencies.

Communication Technologies for Infrastructure

Many types of communications technologies are routinely used specifically to support other kinds of infrastructure. The degree of flexibility originally incorporated into the design (including connectivity) and deployment of those technologies influenced the extent to which they could perform extraordinary functions and meet the needs of their users immediately after the disaster. The response of the telecommunications sector occurred at many levels, reflecting the sector's many different technologies and services. The technologies covered here include wireless communications, the internet, conventional phone lines or land lines, and radio, recognizing, of course, that a variety of sub-types of technologies exist within any one of these areas. Only a few of the many types of communications technologies and their flexibility are described below, although the research (Zimmerman, 2003b) undertakes a more extensive analysis of this sector as it relates to the support of other infrastructure.

Wireless Communications

Restoring cell phone communications undoubtedly had a high priority, given the dependence on and prevalence of use of cellular devices for the communication requirements of other forms of infrastructure. This usage is reflected in part by the escalation in the use of cellular devices and the facilities supporting them over the past decade or so (for nationwide trends before September 11th see Zimmerman (2001) and Cellular Telecommunications and Internet Association (2001)). Three measures discussed below for wireless communications reflect how the degree of flexibility built into the original system influenced the extent of impact and the ability to rebound quickly. The measures covered pertain to the planning for and availability of cell towers to support wireless communications, the ability to meet changes in the demand for additional capacity, and the capability to detect and identify users as part of the immediate search and rescue operation.

The first measure is the design of and planning for physical facilities that support wireless communication devices. In spite of the apparent absence of physical connectivity of wireless devices, these devices depend on land-based towers and sites for signals, and the availability of and impact on these facilities affected cellular communications on and after September 11th. In the case of cell sites, the Wireless Emergency Response Team (2001, p. 12) noted that the number of available cell sites in lower Manhattan after the attacks was limited: although only three cell sites were reported destroyed, about 173 sites were impacted (Verizon's initial figures were five sites destroyed and 160 out of service (Condello, 2001)). In the case of cell towers, mobile cell towers (known as cells on wheels) were rapidly brought into the area to restore the lost service, and Verizon, the provider, (Condello, 2001) reported that 55 such facilities were deployed in the World Trade Center area. Verizon was able to identify, acquire, and take control over resources already in place for other purposes throughout the country. Moreover, it acquired the resources to transport the towers into the city.

A second measure is the ability to meet demand for calling capacity. As is well known, the attack dramatically increased cell phone use. The system was not designed to anticipate such a dramatic rise in usage within the city, regionally, or nationally during and immediately after the attacks. One initial response was call blocking. The providers reported that while normally only 4% of calls are blocked, on September 11th, 92% were blocked (Condello, 2001). However, beyond that immediate time period, Verizon, the major cell phone service provider in the area, reported restoring one-quarter of the capacity within hours of the attacks and 100% within a week (Condello, 2001). Alternate facilities using temporary cabling provided the flexibility to restore capacity. However, had the damage been wider in scale, that approach might have been more limited. A consortium of communications providers and city agencies organized by the New York City Department of Information Technology and Telecommunications and the New York City Office of Emergency Management (OEM) under an agreement called the Mutual Aid and Restoration Consortium 2 Agreement was considered to be an important foundation for post-attack responses by the communications industry. The response might have been more time consuming had such an arrangement not already been in existence before the disaster.

The third measure is the ability and availability of technologies to detect wireless facilities in the rubble and to apply this to the search and rescue operation. The Wireless Emergency Response Team, which was set up within hours of the attacks, led this initiative, with 33 organizations participating (Wireless Emergency Response Team, 2001, p. 7), and provided the flexibility for response that drew upon and very much expanded resources and resource networks set up before September 11th. Detection technologies to identify victims by means of the wireless devices they might have had in their possession (assuming the devices were on) were used extensively by Wireless Emergency Response Team sub-teams in the few days following the attacks to locate victims, although the technical obstacles to detecting wireless devices were serious. Various Wireless Emergency Response Team participants used cell registration patterns, radio emissions from wireless devices of persons trapped in the debris, and database look-up services to track potentially trapped victims (Wireless Emergency Response Team, 2001). Wireless firms outside the immediate area were drawn upon to provide services, such as the Telcordia Routing Administration, with offices in New Jersey, Iowa, and Florida, and this geographic decentralization contributed to at least an implicit organizational flexibility in the system overall. These arrangements probably drew upon relationships established over the years. They not only attempted to meet some of the emergency needs of the moment, but according to the Wireless Emergency Response Team report, provided a core institutional resource for future emergencies. Ultimately, in spite of receiving 120 reports of calls from missing persons in the debris, no lives were saved through this massive and unique effort (Wireless Emergency Response Team, 2002, p. 7), although the approaches developed are likely to advance future response capabilities.

The Internet

One analysis of September 11th impacts defines the internet as “a worldwide collection of networks . . . operated by Internet service providers (ISPs) that accommodates a diversity of applications . . . and numerous more specialized functions” (National Research Council, 2002b, p. 1-1). The internet is not only an infrastructure system in its own right for communications and many other related functions, but it also supports and actually controls other infrastructure by being “embedded” within it (National Research Council, 2002a, p. 135). Similar to other forms of communication, internet use is substantial and has been increasing over the years, although it was reported as being stable between 2001 and 2002. Estimates of the percentage of the U.S. population using the internet by 2001 range from about 54% (U.S. Department of Commerce, 2002, p. 1) to about 72.3% and 71.1% in the following 2002 time period (UCLA Center for Communication Policy, 2003, p. 17). The internet is potentially vulnerable not only through its distribution system but also at a few distinct nodes throughout the system. There are in fact numerous points of entry that could provide the basis for disruption through terrorism (National Research Council, 2002a).

The impact of the September 11th attacks on the internet occurred on many levels. First, on a global scale, the overall impact was relatively minor when compared to other breaches and when the New York City role is averaged globally. Second, in numerous, but often isolated local instances (including within the New York area), internet outages produced profound impacts given the level of dependency of users on it and the absence of alternatives. Third, the internet actually provided an important resource for communications when all other forms of communication became less reliable.

Global impacts of the September 11th attacks on the internet were measured in terms of number of users affected and the time period over which the impacts occurred (in particular, how long it took to return to previous levels). One global measure of internet activity is reachability, defined specifically in the context of the September 11th attacks as "the ability to reach (ping) a select number of sites on the internet in the minutes following the collapse of the first tower" (National Research Council, 2002b, p. 2-4). The results of applying this measure of reachability have been interpreted as showing little sustained impact:

- According to a National Research Council report (2002b), a survey based on approximately 105,000 routes indicated that the impact on the reachability of four internet hosts measured before, during, and after the attacks was relatively minimal. Between the hours before the attacks (a benchmark) vs. 10 a.m. on September 11th, the percent reachability declined 1–7% (depending on the host) and by 7 p.m. that evening had rebounded to within 0.5–1% of the benchmark (extrapolated from National Research Council, 2002b, p. 2-14).
- One provider noted that the overall drop in reachability was about 8% over the day of the attacks, and furthermore, "a loss of this magnitude for an extended period of time would generally be considered a serious problem, but its occurrence for a brief period of minutes is less so—and certainly not unprecedented" (National Research Council, 2002b, p. 2-4).
- In the longer term, the reachability of most routes returned to normal "within 15 minutes of the collapse of the South Tower," however 1–2% of the 105,000 routes did not return to normal for 24 hours after September 11th (National Research Council, 2002b, p. 2-4).

Adverse impacts on the internet that were considered more extreme occurred in the form of localized but often profound outages. Not all of these effects were based in and around New York City or even in the United States, and are in part a function of interconnectivity. For example, 74 U.S. and multinational carriers have equipment in New York and 71 countries have direct links to New York City (National Research Council, 2002b, p. 1-1). New York City carrier hotels (defined as "buildings in which carriers lease space in order to link with other carriers located in the same building") are often the only links for transatlantic cables (National Research Council, 2002b, p. 1-2). For example, as the National Research Council report pointed out, domain name system (DNS) servers are key points in the transmission of information, "the DNS server associated with the .za top-level domain was physically located in New York City," and was damaged during the attacks, resulting in much of South Africa being without internet service (2002b, p. 2-6). Similar kinds of specialized linkages resulting in local outages occurred within New York City and the United States as well, disrupting major services. For example, the New York City Department of Environmental

Protection, the major protector of the city's water supply and wastewater treatment systems, did not have internet access for about two weeks after the attacks, since its internet service provider was located in the Verizon building. As a result, they could only use in-house library resources (Lipsky, 2001). Thus, the considerable concentration of connectivity worldwide in New York City and in particular, through the World Trade Center area, reduced the flexibility of those systems to withstand the effects of the attack, although the ability to eventually reroute to other parts of the internet allowed them to recover. The variety of means of accessing the internet, however, is expected to increase with the introduction of "Wifi" or the "802.11 wireless data standard" (Markoff, 2002).

The internet in many cases played a supportive role in rebounding from the attacks. It proved to be a flexible means of communication for some internet users during and after the attacks when other forms of communication were not viable. For example, when some modes of access to the internet were disrupted, other technologies took their place. Wireless internet services provided by, for example, the Blackberry (of the vendor Research in Motion), introduced in the mid-1990s, were an invaluable internet-based communication tool for government officials and rescue workers. Wireless internet traffic was reported to be 60% higher than normal by 10 a.m. on September 11th (National Research Council, 2002b, p. 2-10), which demonstrates the popularity and responsiveness of this technology. IBM distributed several hundred Blackberry units to city and state agencies and the American Red Cross within days of the attack (Woodworth, 2002). The internet enabled the news media to become a major provider of information as the events unfolded. Traffic to CNN.com in terms of page views increased from a typical load of 14 million to 132 million on September 11th and 304 million on September 12 (National Research Council, 2002b, p. 3-5). CNN was able to meet increased demand for news services by redesigning its websites and adding more servers (National Research Council, 2002b).

Conventional Telephone Lines (Land Lines)

An estimated 300,000 telephone lines and 3.6 million high capacity data circuits were inoperable as a result of the September 11th attacks (Guernsey, 2001, p. G6). As in the case of cell phones, the capacity of the conventional phone system was not flexible enough to compensate for the damaged lines and increased demand, and available phone capacity was soon overwhelmed. Many callers wanted to volunteer their services or provide donations. But many people were unable to phone in, for example, to offer their services to support the health system. They ended up using a more basic means of communication—they arrived at the hospitals to convey their messages. Ackermann (2001) reported that at St. Vincent's Hospital, the nearest hospital to the World Trade Center area, "30,000 people were surrounding St.

Vincent's Hospital to help by the evening. When you plan, think about that. People want to be of help. Eight hundred people lined up to donate blood—there was no administration for that. Twelve Metropolitan Transportation Authority buses took them to other sites in New York City where they could donate blood." A similar situation occurred with the Red Cross, which, according to Lowe and Peek (2001), processed 2,000 offers from 15,570 volunteers. The toll-free calling system, upon which some of the other technologies depended—particularly internet communications—was severely limited in its ability to provide service after the attacks because certain providers had their services disrupted (National Research Council, 2002b).

Through the concerted effort of numerous service providers (not limited to land lines), these communication systems were restored through the use of an extensive above-ground network of cables combined with emergency restoration of power prioritized with respect to users. This ultimately enabled the stock exchanges to function in less than a week after the attack. New sites for operations and the ability to acquire equipment to support them enhanced the rate of recovery. For example, "AT&T established a temporary mobile central office by deploying tractor-trailers with necessary equipment to northern New Jersey. AT&T used telecommunications lines in the tunnels to New Jersey to link service in Manhattan to that temporary facility" (U.S. General Accounting Office, 2003, p. 95).

Radio

Radio played a key part in the communications within the fire and police departments. Many accounts not only of September 11th but of other emergencies as well point to the fact that the flexibility of communications between the New York City Fire Department and New York City Police Department were inhibited by profound cultural differences between the two (Dwyer et al., 2002). In some cases, the technology reflected these differences in that radios operated at different frequencies that made communication between the two departments impossible, except at a relatively high level in the organizations. This has been extensively analyzed in terms of both the technological and managerial dimensions of the problem, including how flexibility can be incorporated into the redesign and use of those communications systems.

Electric Power

Electric power became perhaps the critical link to the viability of infrastructure during and after the attacks, and infrastructure users were not always aware of this. For example, for communications infrastructure, electric energy was needed to run cooling facilities or enable pulses of light to be sent or received over fiber optic cable (National Research Council, 2002b). Major intermediate production and distribution facilities for electricity were damaged. Batteries and generators were used as backup power, but this was often limited for a number of reasons. Batteries failed or eventually expired. Temporary or backup generators were difficult to start, had environmental effects related to the use of diesel fuel (Zimmerman, 2003a), or ran out of fuel and getting fuel to them was difficult given the restricted access to lower Manhattan. While production, transmission, and distribution systems for electric power in lower Manhattan were inflexible in being resistant to the immediate impacts of the attacks, they proved to be flexible thereafter, during recovery or restoration. In the days and weeks after September 11th, electric power was restored at least on a temporary basis by rerouting power from other areas, often with temporary cables, backup facilities, and using mobile facilities such as generators.

Production and Transmission

Substation transformers are a key component of the electrical system. In lower Manhattan, substation transformers step down voltage from 138,000 volts for easy consumption, and 14 operating transformers and six spare transformers out of a total of 355 in New York City and Westchester were located in lower Manhattan at two locations: 7 World Trade Center and the South Street Seaport (New York State Urban Development Corporation, 2002, p. 12-10). Half of that capacity was destroyed in 7 World Trade Center (New York State Urban Development Corporation, 2002, p. 1-2). In spite of the initial vulnerability due to the high concentration of substations in the World Trade Center area, the response reflected a considerable amount of flexibility in terms of the ability to identify, obtain, and deploy additional resources. In the immediate short term, mobile generators were moved in similar to the way in which mobile cell towers were moved in to provide a short-term solution for wireless communications. A vendor supplied over 100 of these generators. Since the vendor routinely supplies such portable generators for emergency power, the units were on hand. This reflected one key criterion of flexibility—an organizational and managerial structure with the ability to identify, acquire, and deploy resources quickly at least to provide short-term needs. As portrayed in the environmental assessment for the rebuilding of 7 World Trade Center, over a longer period of time (to the summer of 2002), the spare transformer vaults from the South Street Seaport site were put into operation and power from other locations in Manhattan enabled some of the lower Manhattan load to be serviced but used up much of its local spare capacity. In the long term, a permanent solution that was put forth is the rebuilding of the two substations that were lost, along with the reconstruction of 7 World Trade Center. This is expected to restore pre-September 11th levels as well as provide for a 1% increase in power (New York State Urban Development Corporation, 2002, p. 1-2, 1-3). Thus, the concentration of transformers in the substations in 7 World Trade Center led to a wider initial impact than might have otherwise occurred. However, the recovery was hastened by the existence of spare power at other locations and in the longer term, the locating of a new building where 7 World Trade Center had been has provided a site for new power and backup capability for lower Manhattan. Institutions adapted to the situation as well. The city's land use and environmental review systems expedited the reviews required to speed up construction of the new building at the 7 World Trade Center site to house the new substations (New York State Urban Development Corporation, 2002).

Distribution

"The Consolidated Edison Company, which provides New York City's electric power, has approximately 102,000 km of primary and secondary electric distribution cables over 1700 km^2, making it the most concentrated in the world" (O'Rourke, 2001). Moreover, the energy density at the World Trade Center site was also extraordinarily high. To compensate for the destroyed distribution lines, Con Edison was able to provide an estimated 36 miles of overland distribution lines as a temporary measure in order to connect the area to alternative sources of energy, and the last temporary cable was removed on May 23, 2002 (Armistead, 2002). According to Con Edison, 98% of the 13,000 customers without service after September 11th had their service restored by means of the temporary cables (Armistead, 2002). The ability to draw power from other areas of their system through temporary distribution lines also contributed to the ultimate restoration of power. Thus, while the considerable density of lines in the area increased the damage, the proximity and similar density of the street system enabled temporary overland cabling to restore some of the lost capacity in the short term.

Water

Two water supply functions were critical immediately after the September 11th attacks. One was ensuring that the supply was adequate for the users whose services were disrupted, particularly for emergency responders for fire-fighting. The other was preventing water from creating floods, and potentially massive ones, if the bathtub was breached in a serious way.

Water Usage

As a result of the attack at the World Trade Center site, about eight to ten water mains and related facilities were ruptured. The broken water lines ranged in size from 16-inch to 24-inch mains (Corley, 2002). New York City consumes about 1.4 billion gallons of water a day. Although the amount lost was a small fraction of this daily total, it was concentrated in a very dense area of the city, constituting a substantial part, if not all, of the water supply of that area. Apparently, neither the quality nor quantity of water supplies throughout the rest of the city was affected. Water was restored later that evening since the city had the flexibility to tap alternative water distribution lines (Figure 1).

In general, dense matrices of pipes are more flexible in securing a water system from the effects of breakages than a branched or linear pattern that has fewer interconnections. Zimmerman (1999) compared the New York City and northeastern New Jersey systems in this regard, noting that when water main breakages occur in New York City, which has a matrix system, outages are usually shorter in duration than in northeastern New Jersey where branched, linear systems provide few alternatives other than bringing in bottled water while a single line is repaired.

The first objective for the provision of water immediately after the attacks was to restore water for fire-fighting at the World Trade Center site. The fires ultimately proved to be inaccessible in the short term to most of the traditional fire-fighting capability. However, the flexibility of the system to bring water into the area in alternative ways was reflected in a range of efforts. These included volunteer bucket brigades, distribution systems for fire-fighting operated by the New York City Department of Environmental Protection through its conventional water system, and the New York City Fire Department fire boat system, which can be connected to either the city's system or the Hudson River. In order to restore water in the city's system for firefighting, the city used a guideline of 40 pounds per square inch to restore pressure after the breakages, and eventually attained that level from a starting point of practically zero due to the breakages. This pressure was restored the day of the attacks due to the city's ability to identify, isolate, and seal off leakage through a systematic series of valve shutoffs and the flexibility to draw water from alternative lines to compensate for the loss of other lines. However, the city's fresh water system was neither of sufficient quantity nor close enough to the fires to provide enough water. Another water source, provided by the fire boat system run by the New York City Fire Department pumping water from the Hudson River, was drawn in to put out the fires. Ultimately, the location of some of the fires and their intensity prevented them from being extinguished for many months.

A second objective for the provision of water met by both the New York City Department of Environmental Protection and the New York City Fire Department pertained to water for dust suppression and for construction needs in general.

A third objective was the provision of water to area residents once rehabitation of the area occurred. Here, quality of the supplies as well as quantity was of critical importance. When water supply lines are breached, an influx of contaminants into the pipes is potentially possible. The New York

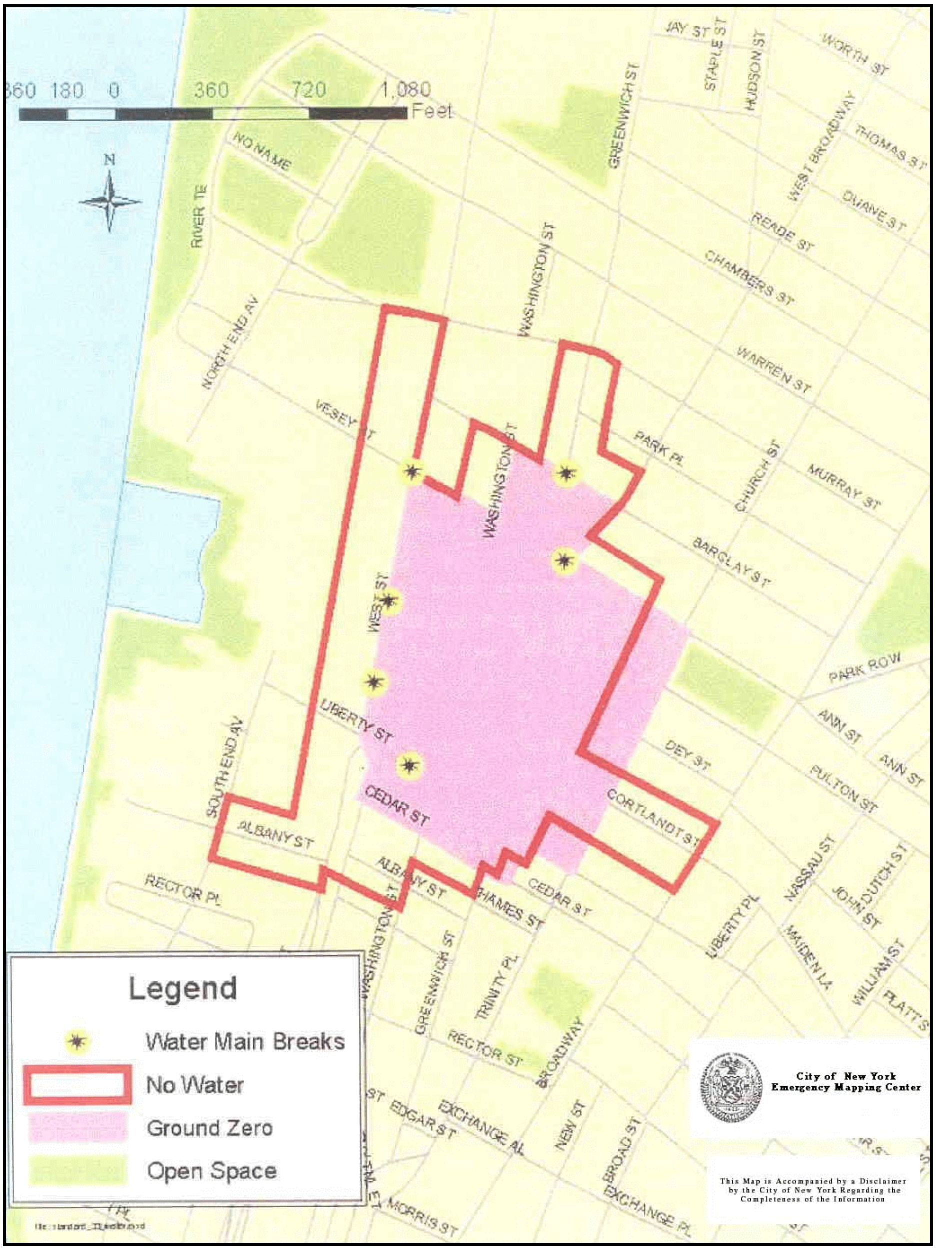

Figure 1. Water outages as of 3:00 p.m., October 7, 2001.
[City of New York, Emergency Mapping Center, Office of Emergency Management]

City Department of Environmental Protection tested the purity of the supplies, and water quality at the time of rehabitation was considered to be meeting water quality standards.

Flood Prevention

A second water supply issue was preventing flooding. One critical flooding problem occurred at the Verizon building at 140 West Street, which was flooded from one of the water main breaks. Another water problem, not directly related to New York City Department of Environmental Protection functions, was the rampant flooding of the Port Authority Trans-Hudson (PATH) tubes from a number of sources. “Flooding of the PATH tunnels was caused by a combination of factors, including rupture of two 1675-mm-diameter pipelines, which circulated cooling water from the Hudson at the World Trade Center Complex, as well as broken water mains, water from fire hoses, and leakage from breaches in the World Trade Center Complex basement walls. Valves were closed to shut off water from the cooling pipelines within a few hours of attack. The northern PATH tunnel was fully flooded at its lowest elevation, with water at station platform level in Exchange Place Station in New Jersey. Water was pumped from the tunnel at a maximum rate of approximately 11,350 liters per minute, and a concrete bulkhead was established at Exchange Place Station to prevent further water ingress on the New Jersey side” (Anonymous, 2002). One of the criteria for flexibility—that of being able to rapidly assemble resources—was met in the sense that the Port Authority had access to the Metropolitan Transportation Authority’s pump with its 6,000-gallon-per-minute capacity for its immediate need to prevent flooding, though the more long-term solution was the installation of concrete plugs (Langewiesche, 2002, pp. 70–71). The Metropolitan Transportation Authority maintains the pump for flooding problems from rainstorms, high water table, water main breaks, and other sources of water into its system.

Transportation

New York City is renowned for the variety of ways to travel, and this became a key resource to attain flexibility in the movement of people and goods during and after the attacks. A number of measures reflect the dramatic adaptability of the transportation system. These measures included those that were user-oriented, such as numbers of passengers and trips. Others pertained to the physical system and its ability to expand to meet the travel demands of people by enabling passengers to shift among different modes of transport.

Waterborne Transportation—Ferries

Ferry service provided the flexibility to move people rapidly away from the site on September 11th, and provided ongoing transportation in the months that followed. Ferry service was critical to the movement of New Jersey residents to New York City and back after September 11th. For example, through the end of November, total ferry ridership increased 27.8% with variations of this average for public and private facilities (calculated from Lee, 2001).

According to some people, long-term reliance on ferry service will have to address questions about differences in the safety standards that ferries have to meet relative to other forms of transportation and the effect these differences may have on passenger safety. Such standards cover the areas of fire protection, preventive maintenance, and backup communications systems (Wald, 2002) and the loading and distribution of passengers relative to capacity. Also, as one would expect, uncertain weather conditions will require that alternative means of travel be available.

Transit—Passenger Transportation

New York City and the region are served by an extensive system of long-distance and commuter rail lines and local transit services. These systems, from long-distance rail to local trains and buses adapted their services dramatically in the aftermath of September 11th to accommodate customer needs after an initial system shutdown. It was the initial, pre-September 11th flexibility in the design and management of those systems to allow a considerable amount of rerouting that contributed to such a rapid post-September 11th response.

Long-distance rail service—Long-distance rail service returned during the evening of September 11th after a general shutdown of all service in and out of Manhattan earlier that day. Amtrak, the main long-distance provider, created a critical alternative to air travel when airlines were shut down for many weeks after the attacks. Key long-term issues will be the relative roles of air travel and Amtrak in providing northeast corridor transportation services and the ongoing concerns about the effect that uncertainties in federal subsidies will have on Amtrak's performance. The condition of Amtrak's facilities will undoubtedly play a role in any systematic relative risk analysis of Amtrak vs. other modes of long distance travel. In particular, questions have been raised about the condition of the tunnels through which Amtrak travels near its main terminals, namely New York City's Pennsylvania Station. The federal government announced $78 million to improve the tunnels for fiscal year 2003, which will undoubtedly reduce the uncertainties in this area.

Local transit and commuter rail service—The Port Authority TransHudson (PATH) system, New Jersey Transit, and the Metropolitan

Transportation Authority and its subsidiaries (Metro North and the Long Island Railroad) provide these services. They responded in many ways immediately after the September 11th attacks.

First, the ability to reroute trains quickly while the attacks were occurring was a clear success story. As a result, service was restored that evening. The ability of the Metropolitan Transportation Authority to reroute subway trains around or away from the damaged site, although producing some delays relative to normal service, was a testimony to the inherent flexibility of a multi-route transit system that has existed for close to a century. The ability to reroute trains is built into its multiple track system used for normal operations and anticipation of routine service outages, and this enabled three trains to be converted into shuttle services in the months following September 11th. The ability to rapidly reroute trains as well as the fact that restrictions on surface transportation led many to use transit systems shows up in the pattern of travel. Month-to-month averages on the larger transit systems show a clear pattern of recovery at least in the short term (Table 1).

Table 1. Change in average weekday transit ridership, 2001.

	August—September	September—October
MTA (Subways)	-6.4%	+11.9%
PATH	-23.8%	+10.1%
NJ Transit	-4.6%	+6.7%

[Calculated from Metropolitan Transportation Authority information.]

Second, however, station capacity proved to be inflexible to the changes in ridership. For example, in the PATH system when the northern routes compensated for the loss of the World Trade Center station, station capacity at those northern locations was soon overwhelmed beyond the point of being able to provide comfortable, and to many, safe and adequate service. Ridership at the Ninth Street station increased from 4,100 to 8,900 and at the Christopher Street station increased from 3,600 to 7,400 (Dunlap, 2002, p. B3) in a matter of days. Expansion of station capacity does not come easily, since increasing the number or relocation of stairways does not typically meet with community approval (Dunlap, 2002, p. B3).

Local bus service—Although bus traffic was initially sharply curtailed in the area to reduce street congestion, emergency bus routes were eventually provided to enable emergency workers, other workers, and eventually residents to access the site.

Surface Transportation—Roads, Bridges, and Tunnels

Massive traffic congestion along surface transportation links needed for rapid access to the site by emergency responders typically occurs in disasters, and unlimited roadway access creates the added problem of security. To avoid this, the city, state, and regional authorities adopted two strategies. The first was to shut down roadways in and out of the city as an initial response to the catastrophe. In the months following the attacks, the New York City Department of Transportation had to invoke other roadway shutdowns for a variety of reasons including the repaving of some 37 miles of roadway encompassing about 600 streets (Haberman, 2002, p. 14), relocating utilities, and security. Although the transit system had similar shutdowns, these were lifted much sooner than the road system shutdowns. While the immediate roadway shutdowns provided flexibility for movement of priority vehicles, it obviously limited the full utilization of resources that normally flow in and out of the city, producing an initial impact on the transport of supplies to residential and commercial customers. The second strategy was traffic management, for example, invoking single occupancy vehicle (SOV) lane restrictions.

Thus, many institutional mechanisms for transportation supported flexibility in routing of people immediately after the attacks and for many months afterwards.

Debris Removal

Debris removal was a critical part of the rescue operation as was the recovery of human remains. Much of the emergency site restoration and the search for human remains there could not proceed without debris removal. Over the course of the eight months since the initial attack, debris removal was estimated at 1.56 million tons—equivalent to the total solid waste generated in the city over a month or the municipal solid wastes generated over four months. The ability to undertake such an additional burden was astounding. Of all of the infrastructure activities that took place, debris removal was perhaps the best example of the flexibility of a very diverse set of resources to come together in a crisis to solve the immediate needs of the public.

By May 2002, debris removal was completed more quickly and less expensively than originally expected. In spite of the many demands placed on the process by the need to maintain the structural stability of the area and to allow the maximum opportunity to uncover bodies, debris removal proceeded at a relatively constant pace, with holiday periods being the only exception. The delicate connections among the many different players such as equipment suppliers, construction contractors, and regulators of waste removal to provide rapid debris removal reflected an extraordinary degree of flexibility given the complexity and uncertainties in the debris removal process.

First, the flexibility to obtain large earth-moving equipment from some of the largest construction companies in the country for site excavation invoked a very large network of construction firms that could be tapped quickly and continuously due to a long-standing tradition of heavy construction activity in New York City. At the time the September 11th attacks occurred, some of the largest construction projects in the country were in progress in New York City, such as the Third Water Tunnel. The availability of the construction industry as a resource is reflected in a very dramatic and symbolic act that took place when news of the World Trade Center attacks spread among the workers: many construction workers left their work sites and proceeded immediately to the World Trade Center. Second, the proximity of the World Trade Center site to a waterfront and a tradition of using barges for waste transfer afforded the opportunity to accommodate large barges for debris shipments. The community adjacent to that waterfront was willing to accept the inconveniences at least in the short term. Third (and related to the second condition), was the flexibility afforded by expedited permitting to excavate nearby waterfront areas to allow the rapid removal of material by barge. Fourth was the city's ability to reopen a portion of the Fresh Kills landfill for debris disposal, even though Fresh Kills had received its last barge shipment in March 2001 and its closing had been awaited and negotiated for years. In addition, a steel-recycling network was tapped to receive the steel. This met with considerable opposition from engineers trying to salvage some of the steel for research, for example, to understand its behavior under the very high temperatures to which it was exposed at the World Trade Center site (Astaneh-Asl, 2001). Fifth, JFK airport was adapted to provide storage capacity for some of the larger, intact pieces of debris such as PATH trains that were being salvaged.

Thus, the process of debris removal reflected an ability to tap resources along the entire chain of debris removal activities.

Policy Recommendations

Flexibility as a Measure of Infrastructure Performance in Times of Crisis

Measures of flexibility reflect user and community expectations for infrastructure services that are important inputs into future design and operation for enhanced resiliency and security. Three indicators of or criteria used in this research for flexibility that emerged from the responses to September 11th provide important guidance for policy, and these criteria provide a simple way of organizing and understanding the subtleties of post-disaster events. A summary of the application of these criteria to September 11th infrastructure responses based on the results of the research to date is given below.

Alternative Routes and Alternative Production Locations

In a number of cases, interdependencies among service providers and their support services limited flexibility and led to disruptions that might have otherwise been avoided, yet measures of infrastructure service response after the disaster indicated that public services were able to draw upon alternative means to meet public needs. Mobility in production and distribution units proved to be a key factor in the ability to rebound quickly, as provided, for example, by mobile generators, cell towers, and flexible distribution lines for the temporary restoration of water, energy, and communication. Immediately after the disaster, for example, distribution networks were, in many cases, put in place to provide and connect users to emergency services for power, water, and communication, because service providers could move equipment from one place to another and provide connections quickly. Temporary cables were rapidly deployed to provide these services on a short-term basis, often outside of the city, for example, into New Jersey. Public transportation systems showed extraordinary ability to redirect traffic, and enabled the city's population to keep moving. Production or critical transmission points are also critical to avoiding vulnerability and supporting distribution networks. Greater flexibility in these systems would have enhanced their role in the recovery effort, for example, having less spatially and functionally concentrated electric power substations and telecommunication domain name servers.

Identification, Acquisition, and Management of Resources

Both government and industry utilities were able to quickly identify, acquire, and manage resources for emergency response in the short term. In some cases, the resources were already available in the form of spare parts at nearby locations (e.g., the Con Edison substation transformers). In other cases, the resources had to be brought from very long distances, but the knowledge of the location of those resources and the ability to obtain them was already in place. Utilities were able to obtain temporary generators and cell phone towers (deploying 55 "cells on wheels"), miles of cable and pipe to construct overland utility networks for land lines, wireless and internet services, construction equipment for debris removal, and mobile temporary offices. Most importantly, they were able to tap the human resources needed to put these facilities in operation.

The ability to draw upon organizational resources was critical to obtaining the physical supplies and facilities and identifying those in need. What became clear was that successful organizational arrangements, both informal and formal, were those that had existed before the disaster or at least where linkages among the individuals had existed that could be quickly mobilized. Examples were numerous. In the telecommunications industry, the Mutual Aid and Restoration Consortium agreement among private vendors and city agencies, the Wireless Emergency Response Team, and the financial group of about a half-dozen vendors all had existed or had informal liaisons before September 11th. The GIS mapping unit, which proved valuable to the rescue and recovery effort, was formed from informal professional groups that had professional associations before September 11th. Likewise, the debris removal operations drew resources from the construction industry, whose companies were already very familiar with one another through professional networks.

Information Transfer

Transferability of information for the purpose of reducing human exposure to the attacks, and hence its consequences, was extremely limited by the capacity and compatibility of communication networks in spite of the fact that facilities were made available to support expanded capacity. Information transfer is a vital dimension of emergency services, and more attention is needed in this area.

Understanding Infrastructure Interdependencies as a Key to Infrastructure Flexibility

Flexibility intended to increase the effectiveness of infrastructure performance can backfire, having the opposite outcome, if not approached from a systemwide perspective that takes into account interdependencies within and among infrastructure systems and between infrastructure and social systems.

Infrastructure systems are interconnected both spatially and functionally, and the degree of interconnectedness tends to increase with population density. Interconnectedness has both advantages and disadvantages. The advantages in terms of economies of scale are well known. The disadvantages are that interconnectedness can generate cascading failures not only among infrastructure systems (O'Rourke, 1993) but also between infrastructure and social systems—the failure of one system creates failures in others.

Many of the infrastructure systems described individually above were highly interrelated, and flexibility has to be evaluated systemwide to capture the impact of such interconnectivity. Numerous telecommunications providers, for example, had facilities that were connected both functionally and physically through the World Trade Center site that were disrupted along with facilities and services provided at that location.

Moreover, communications and other infrastructure depended on electric power provided by Con Edison facilities, which was also concentrated in that same location and forced many of the systems to seek alternative routes and draw on alternative resources in order to recover. In the case of electric power, Guernsey (2001, p. G6) points out that “some of those multiple lines travel the same conduits to the same routing centers” and the conduits or routing centers were not redundant enough to withstand the damage. “Redundancy in some instances may only be apparent or limited to a given part of the system only to have a critical link moved to a different point in the system” (Guernsey, 2001, p. G6).

Examples where water systems were connected to other infrastructure and caused failures across different kinds of infrastructure as a result of the September 11th attacks also illustrate the downside of these interconnections. On September 11th, water damaged telecommunication infrastructure at 140 West Street, train lines were flooded by water from various sources, and flooding of electric power systems destroyed telecommunications and computer data systems that were connected to those power systems (Zimmerman, 2001; Guernsey, 2001).

Looking Backwards to Look Forward

One of the reasons for many of the successes in the short term was that many responders used their experiences from previous situations that appeared to at least have similar elements to what happened on September 11th. These past experiences were both positive and negative. Examples of the kinds of previous experiences that may have and certainly could have contributed to the knowledge and experience supporting the responses to and recovery from the September 11th attacks are listed below.

- New York City has 500–600 water main breaks a year, a few involving pipes and volumes of water lost greater than the amount of water lost on September 11th. However negative these experiences seem, they at least provided the city with a protocol for responding to water main breaks that was used on September 11th and the days following.
- Con Edison has had major outages from underground fires and other origins that often have greater consequences than what was experienced on September 11th. Response capabilities from these experiences in part provided Con Edison with the ability to at least respond in the short term.
- The transit system’s experience with train failures, including water and electric failures that contribute to train failures, has built considerable redundancy into the system over decades, which paid off in being able to enable the transit system to rapidly rebound in the short term.

- When new information and communication technologies fail, operators typically respond with older, more familiar technologies. The New York City Fire Department did this with respect to radios. Water managers routinely do this when information technology controls fail, and they have to use manual overrides to operate valves and treatment plant controls.

Integrated Decision Tools

Finally, in making the transition from past behavior to action during emergencies and from emergency action to long-term solutions, many tradeoffs have to be made in operationalizing the concept of flexibility and ensuring that it is applied system-wide. Many examples of these tradeoffs were alluded to above. In order to accomplish these tradeoffs, traditional methods for decision-making need to be expanded. For example, the analytical capabilities of various existing techniques need to be integrated. These individual techniques include risk assessment (Haimes, 1998; National Research Council, 1994), decision analysis (Clemen and Reilly, 2001), environmental impact assessment (Gregory et al., 1992), life cycle engineering (O'Rourke, 1993), risk management (Stern and Fineberg, 1996), and the social psychological approaches to risk perception and the application of all of these techniques to the behavior of infrastructure services and their users in extreme events (Slovic, 2000; Bier et al., 1999; Mileti, 1999). First, these individual techniques gain more strength if they are integrated and act in concert with one another. Second, more applications to infrastructure are needed. Some applications to infrastructure exist, for example, in the area of risk assessment of engineered structures (Haimes et al., 1998; Lave and Balvanyos, 1998; Zimmerman and Bier, 2002). Third, and most importantly, these capabilities need to be designed carefully in a way that can be communicated appropriately and be useful to front-line decision-makers.

Longer-term Issues: Security as a High Priority

Security has added a whole new dimension to the provision of infrastructure services, yet it is one that can be made compatible with existing infrastructure. Infrastructure is essential to moving emergency personnel, food, shelter, sanitary facilities, and medical services into a devastated area and moving victims out in the short term. In the long term it is critical to moving debris and other waste out in an environmentally sound manner and getting equipment in for restoration and site. Thus, the need to protect and secure these infrastructure resources is obviously critical.

Estimates after September 11th are in the billions of dollars for securing water and transportation infrastructure alone, and leveraging through flexibility can potentially provide savings. In the area of water supply, the following Congressional testimonies reflect the magnitude of some of these needs:

- $4.7 billion in fiscal year 2003 alone for vulnerability assessments and security systems for the nation's water supply and wastewater treatment systems (Water Environment Federation, 2002, p. 1).

- $267 million in the first year plus $65 million annually will be needed by the Corps of Engineers for security upgrades (Ichniowski, 2001).

- $5 billion for infrastructure work and $100 million for vulnerability assessments will be needed in total for the city of Boston alone, according to the Boston Water and Sewer Authority (Ichniowski, 2001).

A key policy issue is that in light of the very large investments necessary for security, how security can be designed in a way that it meets multiple objectives rather than one. That is, whether or not security needs can be met that also support improved condition and resistance to the adverse effects of natural hazards. Moreover, the use of information technologies is increasing to manage infrastructure and also to support security. Detectors or sensors, for example, will become more common in managing and protecting infrastructure. Accompanying this technology are uncertainties in interpreting the data and matching the data to what we want to know. A final issue is the reliability in the coverage of such devices relative to our expectations.

Initial Observations about Flexibility and Infrastructure Policies in Times of Crisis

The concept of flexibility provides a valuable framework for evaluating and explaining the response and recovery of vital infrastructure services during and after the attacks on the World Trade Center. This concept applies to both physical and social systems involved in meeting the needs of users of infrastructure, and the criteria that define it involve the ability to obtain alternative production systems and distribution routes; the ability to rapidly identify, acquire, and manage resources and transfer information; and the ability to promote the networks to sustain these capabilities. Key policies to improve the adaptability of infrastructure services under crisis conditions would benefit from explicit use of measures of flexibility to enable agencies to manage their services in a crisis and, in particular, to gain access to resources and support connectivity with other functions in order to restore services.

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